

5.3 Small Crack Behavior

Damage tolerant structural design requires that a pre-existing, initial crack at a critical location in a structural detail must not reach the critical size required to maintain the minimum load bearing capability during its design life. The design life of a damage tolerant structure, i.e., the number of flights required to grow an initial crack to a critical size, is calculated from the crack growth relations discussed in Section 5.5. The initial crack size assumptions for structural details are discussed in Section 1. For structures with close tolerance fasteners, the initial primary damage size is 0.05 inch. A crack size of .005 inch for continuing damage at the holes is recommended. These assumptions for initial crack lengths are based on NDI capability of the designer. With improved NDI techniques, cracks smaller than 0.05 inch can be detected. The small crack growth behavior discussed here provides guidelines for crack growth analysis if an initial crack smaller than 0.05 inch is assumed in the damage tolerant design of structural members.

5.3.1 Small Crack Growth Analysis

The design guidelines and linear elastic fracture mechanics based life prediction methods discussed in this Handbook are applicable to long cracks only. From mechanics considerations, the development of crack occurs in three distinct stages: crack initiation, small crack development and long crack progression. Crack initiation (and nucleation) is not discussed in this Handbook because of the required assumption of a pre-existing structural crack. A long crack has a dominant singularity in the continuum domain. A crack is considered small when it is smaller than the long crack. For a small crack, the similitude rules break down. The crack size is comparable to one or few grains, the plastic zone size is not small compared to the size of the crack and the assumption of a linearly elastic material at the crack tip region is not realistic.

It has been experimentally observed that small crack growth behavior is different from the behavior of long cracks. However, the upper limit of the crack size below which the small crack effects start and the conventional long crack growth behavior resumes is not well established. The crack lengths from .040 in. to .070 in. have been proposed. The following observations of small crack behavior from experimental data have been reported in the literature.

1. It has been demonstrated from the crack growth data under both the constant amplitude loads and the spectrum loads that the small crack growth rates are higher than those for long cracks. Higher crack growth rates result in non-conservative predictions of fatigue life.
2. A small crack can grow even when the applied stress intensity factor is well below the threshold limit. The threshold stress intensity factor range is dependent on the stress ratio.
3. The experimental results show that the small crack effects are more pronounced at extreme values of stress ratios.
4. The behavior of small cracks initiated at holes is different from the behavior of small cracks in un-notched materials.

Because of these differences, an understanding of the mechanics of small crack growth and mechanisms of cracking in the small crack regime is necessary. The structural designer should have the appropriate design tools to incorporate the effects a small crack may have on crack growth rate and resulting life prediction. The small crack effects are present either because the similitude rule for LEFM application to crack growth breaks down or inappropriate evaluation of the damage parameters such as the stress intensity factor K or the J -integral used for steady state

crack growth rate prediction. The similitude rules are a set of requirements on structural crack geometry and the mode and extent of crack-tip deformation of a material under loading. A discussion of similitude rules is presented by Leis, et.al.[1986].

The small crack effects have been observed in both notched and un-notched specimens. The un-notched small crack growth behavior has been attributed to crack grain boundary interaction effects not accounted for in the fracture mechanics based predictions of small crack growth. In the case of long cracks, the crack growth in the plastic wake is averaged over many grains. It has been argued by Leis, et al. [1986] and Blom, et al. [1986] that the difference in crack growth at notches is not due to the breakdown of similitude rules but inaccurate calculations of the stress intensity factors.

Based on observations of small crack growth in 2024-T3, Blom [Blom, et al., 1986] reported that the short crack effects are due to plasticity induced crack closure and roughness induced closure effects. He also concluded that in this material a crack should be at least four grains in length before qualifying as a long crack. In Newman's [1992] study of small cracks in 2024-T3 and 7075-T6 specimens, the crack closure transients have been found to be the cause of crack growth effects. There is transient behavior of crack opening stress as the crack progresses from small crack size to long crack. At higher stress ratios (stress ratios over 0.5), the crack may be assumed to be open and thus has no significant effect on crack opening stress. At higher negative stress ratios (i.e. at $R=-2$), the effects have been found to be more significant. A fatigue crack growth analysis computer code "FASTRAN" based on plasticity induced closure has been developed and currently available at NASA Computer Management and Software Information Center.

Nagar [2002] studied small fatigue crack growth behavior at pin-loaded holes in structural joints where small cracks are often observed. Experiments were conducted on 2024-T3 specimens with 0.003 inch single, thru-radial cracks. The rectangular panel specimens with two collinear central cracks and doublers of varying stiffness were joined by close fit titanium pins. The doublers provided the variation in load transfer rates at the fasteners holes. The loads of constant amplitude with marker bands and spectrum loads were applied to the specimens.

A comparison of structural joint small crack growth data with FASTRAN predictions show that FASTRAN predicts small crack behavior under constant amplitude loading reasonably well. However, the plasticity induced closure based predictions by FASTRAN do not correlate with the small crack growth data under periodic over loads (marker bands) as well. The predictions of small crack life under spectrum loads (EIFS) were even farther off. In general, the crack growth rates are lower than predicted. Thus there is a question whether FASTRAN can be employed reliably to predict small crack growth in joints with loading histories.

The experimental strain data developed during this program also indicated that the load transfer rates for steel doublers can not be predicted using the same technique as used in NASTRAN which have been used for calculations of fastener load transfer with aluminum doublers. This study was conducted under a co-operative FAA/Air Force/Boeing program and the details are available in an Air Force Research Laboratory Report [Nagar, 2002].